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# THE EXIT OF NEUTRONS DURING A NONRESILIENT INTERACTION OF NEUTRONS WITH ENERGIES OF 14 MEV WITH NUCLEI AND A CROSS SECTION OF REACTION (n, 2n)

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## Abstract

The number of $\eta$ neutrons which were created during one act of nonresilient interaction of neutrons with nuclei of a number of elements of a natural isotropic content (Fe, Cu, Mo, Cd, Sn, Sb, Hg, Pb, Bi, U) was measured. Measurements were made by determining the relative change of a complete neutron flux and a weakening of original neutrons after passing through specimens of investigated matter. Thereby, data were also obtained on the cross section $\sigma_{in}$ of a nonresilient interaction of neutrons with nuclei of the mentioned elements. The established values $\eta$ and $\sigma_{in}$, together with a known cross section as a neutron entrapment, were used for the computation as averaged by their isotropic-content cross sections of the reaction (n, 2n) on indivisible nuclei.

The number of $\eta$ neutrons which were created during one act of nonresilient interaction of neutrons with nuclei can be generally expressed by a correlation

$$\eta = \frac{\sum_j \nu_j \sigma_j}{\sum_j \sigma_j} \tag{1}$$

where the summation was conducted by all forms of nonresilient interactions of neutrons, which includes entrapment with the dropping of $\gamma$-quantums or charged particles; nonresilient dispersion, including the processes (n, n$\gamma$), (n, np), (n, n$\alpha$), the processes (n, 2n), (n, 3n), division, etc; $\nu_j$ exit of neutrons during the given elementary interaction; $\sigma_j$ cross section of a corresponding process; $\sum_j \sigma_j = \sigma_{in}$ cross section of nonresilient interactions. It is obvious that $\nu_{n,\gamma} = \nu_{n,p} = \nu_{n,\alpha} = 0$; $\nu_{n,n\gamma} = \nu_{n,np} = \nu_{n,n\alpha} = 1$; $\nu_{n,2n} = 2$; $\nu_{n,3n} = 3$, etc. In the case of slow neutrons $\eta$, it differs from 0 only in the case of nuclei which are divisible with these neutrons and equals $\nu_{n,f} \cdot \sigma_f/\sigma_{in}$.

The independent measurement of $\eta$ is a means for checking the accuracy of measurements of other values which are included in Formula (1), if they are known, or might serve for the determination of one of these values. For instance, if a nucleus is indivisible and the reaction (n, 3n) at a given energy of a neutron is impossible, then $\eta = 1 + \frac{\sigma_{n,2n} - \sigma_c}{\sigma_{in}}$. In the case of such nuclei, the measurement $\eta$ might be considered as an independent method of determining $\sigma_{n,2n}$, if $\sigma_{in}$ and $\sigma_s$ are known. Measurements of $\sigma_{n,2n}$ with this method, contrary to the activating method, are possible also in the cases when the isotope which is being created is stable. If the specimen of the elements which is being investigated contains several isotopes, then with the help of this method it is possible to find only the values which are considered in accordance with the isotope contents $\eta$ and $\sigma_{n,2n}$. In this work is measured the value $\eta$ and $\sigma_{in}$ for neutrons with energies of 14 mev in the case of 10 elements.[a]

The method which was used for measuring of $\eta$ and $\sigma_{in}$ consists of determining the proper change of a complete neutron flux and in the weakening of the flux of original neutrons after they pass through the specimen. The measurements were within the framework of spherical geometry, whereby the source of the neutrons was placed in center.

The balance of the neutrons after passing through a sufficiently small specimen might be written now as

$$N = N_0 - N_1 + N_1 \eta$$

where $N_0$ is the number of original neutrons, $N_1$ is the number of original neutrons which were subjected to nonresilient interaction, and N is a complete number of neutrons which departed from a specimen.

Since secondary neutrons have a certain energetic distribution F(E) and a detector effectiveness $\epsilon = \epsilon(E)$ which depends on the energy of neutrons, then by 1-1/2 flux of original neutrons, a detector will register the following number of neutrons:

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[a]Recently a number of papers were published which were dedicated to the measurements of $\eta$ on four neutrons. In 1955 a paper (Ref 1) was published in which (by using a method which is analogous to the one which we apply in this paper) $\eta$ was measured on neutrons with energies of 14 mev for 11 elements with a natural isotropic content.

Without a specimen

$$J_0 = N_0 \epsilon_0$$

With a specimen

$$J = (N_0 - N_1)\epsilon_0 + \frac{\int_0^{E_{max}} N_1 \eta F(E) \epsilon(E) dE}{\int_0^{E_{max}} F(E) dE}$$

where $E_{max}$ is the maximum energy of the spectrum of secondary neutrons and $\epsilon_0$ is the sensitivity of the detector to original neutrons.

From this it follows that

$$\eta = \frac{\frac{J}{J_0} - \frac{N_0 - N_1}{N_0}}{\left(1 - \frac{N_0 - N_1}{N_0}\right) \frac{\bar{\epsilon}}{\epsilon_0}} \tag{2}$$

where

$$\bar{\epsilon} = \frac{\int_0^{E_{max}} F(E) \epsilon(E) dE}{\int_0^{E_{max}} F(E) dE} \tag{2a}$$

It is known that a spectrum of neutrons created as a result of the passage of neutrons with an energy of 14 mev through a specimen of heavy matter consists of two groups; whereas, the groups of primary and secondary neutrons do not overlap and $E_{max}$ practically does not surpass 4 to 5 mev. Therefore, in order to determine the corresponding weakening of the original flux $N_0 - N_1/N_0$, a baffle copper indicator was applied which became activated as a result of the reaction $Cu^{63}(n, 2n)Cu^{62}$, and a boric counter with a paraffin block, which was analogous to the one described by Hanson and McKibben (Ref 2), was used in the capacity of a detector by a corresponding change of a complete flux. The sensitivity curve of the counter, which was determined under conditions in which measurements were made, is presented in Figure 1.

The effectiveness of the counter for the original and secondary neutrons was found by means of measurements of the flux D-D and D-T neutrons in an ionized division chamber with layers of uranium.

During the determination of each of these values a number of measurements were conducted, which has made possible the finding of the average square error. This error did not exceed ±1% during the measurements of $J/J_0$ and ±2% during the measurements of $N_0 - N_1/N_0$. The complete error is considerably larger and depends on a number of other factors. The act of the angular anisotropy of the original flux, its energetic nonuniformity, the background of neutron dispersion, etc., on the accuracy of measurements under conditions of our experiments was negligibly small. The error connected with the nonstability of the sensitivity of the counter (Ref 2), taking into account the shape of the spectrum of secondary neutrons, was equal to ±5%. During the measurements of the sensitivity of the counter to neutrons with energies of 14 mev, an essential unknown was added by the insufficiently accurate knowledge of the relation of the cross section of uranium separation under the influence of D-D and D-T neutrons. The error of this relation is included in the complete random error, even if it is actually a component part of the value $\eta$ for all nuclei.

As is obvious from Table 1, the specimens which were used were not small. Therefore, the interaction of the secondary neutrons with the material of the specimen was considered. A corresponding correction was determined by the average cross sections of divisions and entrapment according to the spectrum of the secondary neutrons (the average values of the cross section according to the spectrum were taken for computation) and by the average extent of travel of these neutrons through the specimen. The last one was calculated with the assumption that the angular distribution of secondary neutrons is isotropic. This correction oscillated from tenths to 1.5 to 2% in the case of specimens of various indivisible matter. In the case of a uranium specimen, this correction was 6%. During the calculation of $\sigma_{in}$ (after the weakening of the flux of original neutrons), the correction was evaluated on the numerous flexible neutron dispersions, taking into consideration the increase in length of the path of these neutrons in the specimen.

Table 1. Measurement results

| Element | Layer thickness atom/cm$^2$ x $10^{-24}$ | $\frac{I}{I_0}$ | $\frac{N_0 - N_1}{N_0}$ | $\eta$ | $\sigma_{in}$, barn | $\sigma_{n,2n} - \sigma_c$, barn | $\left(\frac{\sigma_{n,2n}}{\sigma_{in}}\right)_{calc}$ |
|---|---|---|---|---|---|---|---|
| Fe | 0.404 | 1.143±0.004 | 0.560±0.007 | 1.20±0.15 (1.27±0.04) | 1.44±0.04 (1.27±0.04) | 0.26±0.1 (0.07±0.03) | 0.44 |
| Cu | 0.390 | 1.320±0.009 | 0.557±0.012 | 1.34±0.15 (1.187; 1.139) | 1.50±0.07 (1.42±0.04) | 0.47±0.1 (0.24±0.02 | 0.64 |
| Mo | 0.171 | 1.269±0.009 | 0.752±0.014 | 1.64±0.2 | 1.60±0.15 | 1.0±0.2 | 0.79 |
| Cd | 0.212 | 1.403±0.004 | 0.674±0.022 | 1.74±0.2 (1.95±0.05) | 1.87±0.2 (1.95±0.05) | 1.38±0.3 (0.89±0.02) | 0.92 |
| Sn | 0.172 | 1.359±0.004 | 0.730±0.22 | 1.81±0.2 (1.527; 1.539) | 1.83±0.2 (1.96±0.05) | 1.48±0.3 (1.04±0.02) | 0.92 |
| Sb | 0.155 | 1.325±0.006 | 0.751±0.012 | 1.82±0.2 | 1.85±0.13 | 1.52±0.2 | 0.92 |
| Hg | 0.183 | 1.488±0.004 | 0.638±0.012 | 1.86±0.2 | 2.46±0.1 | 2.02±0.2 | 0.99 |
| Pb | 0.157 | 1.468±0.008 | 0.582±0.009 | 1.92±0.2 (1.721; 1.688) | 2.46±0.1 (2.49±0.02) | 2.18±0.2 (1.75±0.04) | 0.99 |
| Bi | 0.134 | 1.414±0.007 | 0.708±0.007 | 1.88±0.2 (1.746; 1.730) | 2.58±0.1 (2.53±0.02) | 2.18±0.2 (1.86±0.02) | 0.99 |
| U | 0.230 | 2.48±0.02 | 0.480±0.015 | 2.8±0.25 | 2.91±0.14 | - | - |

In order to compute the average length of the path of flexible dispersed neutrons, it is necessary to know their angular distribution. It was assumed during the evaluation that the angular distribution has a form in accordance with the idea of a flexible dispersion as well as on the defraction of a rapid neutron with a wavelength of $\lambda(E)$ on a nontransparent sphere with a radius which equals the radius of the nuclei R:

$$\frac{d\sigma_s}{d\omega} = \frac{R^2}{\theta^2} J_1^2\left(\frac{R}{\lambda} \theta\right) \tag{2b}$$

where $\sigma_s$ is a cross section of a flexible dispersion, $d\omega$ is the element of the solid angle, $\theta$ is the angle of dispersion, $J_1$ is the Bessel function of the first order.

Such a method for calculating a correction leads to the decrease of $\sigma_{in}$ by approximately 10% during the weakening of the original cluster which equals 0.5, and approximately by 4% during the weakening which equals 0.7. However, an error in the correction (which depends on $N_0 - N_1/N_0$ at a complete cross section of interaction) is relatively great. In some cases this error cancels the correction.

The measurement results are given in Table 1. The data from the paper (Ref 1) are given in parentheses. The magnitude values of $\sigma_{in}$, which are given in the table, do not include the corrections for the numerous collisions of flexibly dispersed neutrons due to the large indeterminate (with the exception of results in the case of uranium), but the complete error of the result was increased in a corresponding manner. In addition, it is now convenient to compare the uncorrected numbers with the results of the work (Ref 1) in which the indicated correction is also absent. Data obtained in the present work agrees with the results of other authors (Refs 1, 3 through 7) within the limits of the error of the value $\sigma_{in}$.

However, the uncorrected results of the present work coincide with the data of these papers in which corrections on numerous collisions of flexibly dispersed neutrons are considered better than the corrected. This points to the fact that the above indicated method for evaluation of corrections is not sufficiently reliable.

The values $\eta$, which were obtained in the work (Ref 1), are systematically smaller by 10 to 15% than the data obtained in the present work. It is possible that this can be explained by the sharp drop of sensitivity (in the area of low energy neutrons) of the counter (Ref 3) which was used in this work; as a result, the number of registered neutrons in the soft part of the spectrum could have been lowered.

Due to the above, the difference in the magnitudes of $\eta$ of the value $(\sigma_{n, 2n} - \sigma_c)$ in the paper (Ref 1) and in this paper differ in the same manner as $\eta$, but in a large ratio since they are proportional $(\eta - 1)$.

In the last column of Table 1 the relations are given of the cross section of reaction (n, 2n) to the cross section of nonflexible interaction which was computed in accordance with the work (Ref 8) and averaged according to the isotropic contents. In the case of neutrons with energies of 14 mev, the calculated value of the cross section of the process (n, 2n) is a significant part of the entire cross section of the nonflexible interaction, and in the case of heavy indivisible nuclei, it is almost equal to them.

It is possible to compare with these data the obtained relation $\sigma_{n,2n}/\sigma_{in}$ for bismuth, lead, mercury, copper, and possibly also iron. In the case of heavy nuclei, this can be done according to the data of the present work, because $\sigma_c$ is negligibly small (Ref 9). $\sigma_{n,2n}$ was measured in the case of copper in a number of works by means of activation methods (Ref 10). $\sigma_{n,2n}$ can be evaluated in the case of iron if we accept that the neutron entrapment by iron takes place basically on account of the reaction (n, p) (Refs 9 and 10) on the isotope $Fe^{56}$ (propagation 92%). It is impossible to compare the results which were obtained on other materials because of insufficient data on the corresponding cross sections of entrapment. It is possible, however, to mention that the experimental value of the relation is less than the calculated. In the case of the nuclei which were investigated, the variation reaches 25 to 30%; on the heavy nuclei, this variation is on the order of 10%. The variation might be explained by the approximate characteristics of the theory and particularly the method for calculation of temperature of an excited nucleus.

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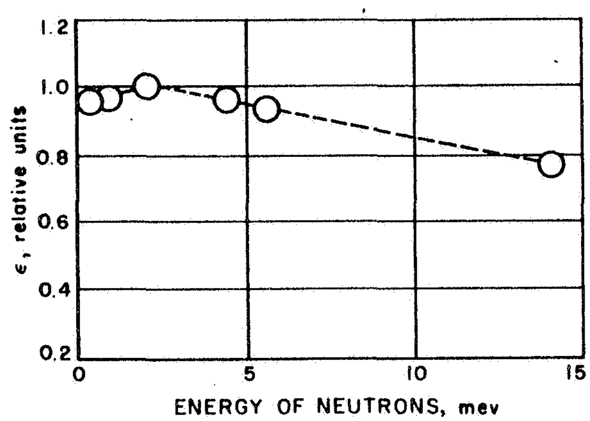


Figure 1. Dependence of sensitivity of counter on energy of neutrons

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